

## Search for Dirac Monopoles\*

HUGH BRADNER AND WILLIAM M. ISBELL

*Radiation Laboratory, University of California, Berkeley, California*

(Received November 24, 1958)

Nuclear emulsions were used to establish the following upper limits for the production of Dirac monopoles by 6.3-Bev protons:

If poles of protonic mass are produced by direct nucleon-nucleon collision, the production cross section is less than  $2 \times 10^{-35}$  cm<sup>2</sup> per nucleon.

If poles of protonic or lower mass are produced by direct or by secondary processes and are subsequently held in matter with a binding energy less than 3 ev, the production cross section is less than  $1.5 \times 10^{-37}$  cm<sup>2</sup> per nucleon.

If poles of protonic or lower mass are produced by direct or by secondary processes and are subsequently held in matter with a binding energy between 3 ev and 20 ev, the production cross section is less than  $10^{-40}$  cm<sup>2</sup> per nucleon.

### INTRODUCTION

IN 1931, P. A. Dirac pointed out that the existence of one free magnetic pole of strength  $\mu_0 = \hbar c / 2e$  would be sufficient to quantize the electric charge of every particle in the universe.<sup>1</sup> In subsequent papers he and other investigators have further explored the characteristics of such a particle.<sup>2-15</sup>

(1) A lower limit on the mass of a monopole can be set at approximately the  $\pi$ -meson mass; virtual poles lighter than this would result in a noticeable change in the Lamb shift.<sup>16</sup> No upper limit on the mass is set; however, poles would presumably have to be produced in pairs, and hence could not be made by the Bevatron if they were appreciably more massive than protons.

(2) The magnetic field at a distance  $r$  cm from a Dirac pole would be  $N(137/2r^2)4.8 \times 10^{-10}$  gauss, where  $N$  is an integer which in this paper we arbitrarily take to be unity. Some unique properties resulting from the high "effective charge" of the poles would make them easy to detect:

Poles would gain energy at a rate of  $300N(137/2)H$  electron volts (ev) per cm when being accelerated by a magnetic field of  $H$  oersteds. The radiation damping during acceleration can be computed in the same way that Schwinger has done for electrons.<sup>17</sup> The rate of loss

would be  $(137N/2)^2$  as large as for unit electrical charge of the same mass and energy.

Poles moving through matter with relativistic velocity would lose energy primarily by direct interaction between the field of the moving pole and the charge of atomic electrons.<sup>12,13</sup> The rate of energy loss would be  $(137N/2)^2$  times the  $dE/dx$  of protons with the same velocity. This rate of energy loss would be approximately constant down to low velocities; then it would fall to zero without a Bragg tail.

Very-low-energy poles are expected to be bound in matter with an energy of the order of chemical binding, *viz.*, a few electron volts.<sup>14</sup> It should be possible to remove them by applying a sufficiently strong magnetic field. The effect is analogous to the rupture of electrons from insulators by strong electric fields.

A monopole should be stable until it encounters a monopole of opposite polarity. We would expect the interaction distance to be small compared with atomic dimensions.

### EXPERIMENTS

#### I

A 0.005-in.-thick aluminum target, inclined 45° from the vertical, was placed in a field of 14.2 kilogauss inside the Bevatron, and exposed to a total beam of  $5 \times 10^{12}$  protons of 6.2 Bev. Dirac monopoles formed at rest in the center-of-mass system would follow a hyperbolic-cosine path as they traveled downstream and "fell" under the influence of the magnetic field. It can easily be shown that the equation for the trajectory of a monopole emitted at an initial angle  $\phi$  from the horizontal would be given by

$$y = A [\cosh(x/\beta_0 A \cos \phi) - 1 + \beta_0 \sin \phi \sinh(x/\beta_0 A \cos \phi)],$$

where  $A = 2\gamma_0 m_0 c^2 / 137eH$ , and radiation due to acceleration has been neglected. Radiation losses of the accelerated pole would introduce a very small correction to this trajectory.

A monopole of single-pole strength would gain an energy of 4.1 Bev in falling the 14 cm to the lower pole

\* This work was done under the auspices of the U. S. Atomic Energy Commission.

<sup>1</sup> P. A. M. Dirac, Proc. Roy. Soc. (London) A133, 60 (1931).

<sup>2</sup> I. Tamm, Z. Physik 71, 141 (1931).

<sup>3</sup> P. O. Grönblom, Z. Physik 98, 283 (1935).

<sup>4</sup> M. N. Saha, Indian J. Phys. 10, 141 (1936).

<sup>5</sup> P. Jordon, Ann. Physik 32, 66 (1938).

<sup>6</sup> M. Fierz, Helv. Phys. Acta 17, 27 (1944).

<sup>7</sup> Pierre P. Bonderet, Helv. Phys. Acta 19, 503 (1946).

<sup>8</sup> P. A. M. Dirac, Phys. Rev. 74, 817 (1948).

<sup>9</sup> H. A. Wilson, Phys. Rev. 75, 309 (1949).

<sup>10</sup> John A. Eldridge, Phys. Rev. 75, 1614(L) (1949).

<sup>11</sup> M. N. Saha, Phys. Rev. 75, 1968 (1949).

<sup>12</sup> H. J. D. Cole, Proc. Cambridge Phil. Soc. 47, 196 (1951).

<sup>13</sup> E. Bauer, Proc. Cambridge Phil. Soc. 47, 777 (1951).

<sup>14</sup> W. V. R. Malkus, Phys. Rev. 83, 899 (1951).

<sup>15</sup> K. Ford and J. A. Wheeler, Phys. Rev. 81, 656(A) (1951).

<sup>16</sup> Joseph V. Lepore, University of California Radiation Laboratory (private communication).

<sup>17</sup> J. Schwinger, Phys. Rev. 75, 1912 (1949).

face of the Bevatron. If monopoles of protonic rest mass were produced, they could have a small motion in the c.m. system, and would strike the pole face in a spot of approximately 5 cm diam at a distance of 13 cm downstream from the target. Nuclear emulsions wrapped in 0.005-in.-thick black paper were placed on the lower pole face to detect any Dirac monopoles that struck there. Emulsions were also placed at smaller distances downstream to detect monopoles down to  $\pi$ -meson mass.

The Dirac poles should be easy to detect, since they would deposit 4 Bev of energy in traversing the black-paper wrapping and 1000  $\mu$  of emulsion.

We achieved low sensitivity to electrons and gamma rays by processing 200- $\mu$  *D*.1 emulsions in *D*-19 developer for 1 hr at 5°C. Sensitivity to highly ionizing particles was checked by observation of natural  $\alpha$ -particle background in the emulsions and by observation of  $\alpha$  particles and fissions from  $\text{Cf}^{252}$  which had been soaked into several spots on the emulsions.

No evidence was found for monopoles produced at rest in the c.m. system, in the mass region between proton and  $\pi$  meson. The 1-in.-wide emulsions would have intercepted about half of all poles of protonic mass if they were produced with spherically symmetric distribution in the c.m. system. If we consider that the proton beam circulating in the Bevatron makes about two traversals through the target, we can set an upper limit of  $2 \times 10^{-35}$  cm<sup>2</sup> per nucleon for the production of Dirac monopoles of protonic mass by primary processes in an aluminum target bombarded with 6.3-Bev protons. The corresponding cross section for monopoles of  $\pi$ -mesonic mass is approximately  $10^{-34}$  cm<sup>2</sup>.

It has been pointed out that parity would not be conserved in the production of Dirac monopoles in nucleon-nucleon collisions.<sup>18</sup> Monopoles produced in the target by secondary processes in the above experiment would not have been detected unless the monopoles had high forward velocity in the laboratory system.

## II

A copper target  $\frac{1}{2}$  in. thick and 2 in. high was placed in the 14.2-kilogauss field in such a position that the proton beam struck the upper edge of the target. Emulsions were placed 7 cm vertically below the bottom of the target. In this arrangement, monopoles of any mass

produced by primary or secondary processes in the target would lose horizontal momentum in less than a millimeter of travel. All south poles would diffuse downward under the action of the magnetic field, unless they were bound too strongly in copper. Upon leaving the target they would be accelerated, and would have  $2 \times 10^9$  ev energy when they struck the emulsion.

We can estimate the maximum binding energy that would permit the removal of monopoles bound to atomic electrons in the target by computing what kinetic energy they would attain when accelerated from rest by a magnetic field of 14.2 kilo-oersteds through a distance of their bound-orbit radius. Using the uncertainty relation to establish this radius, we compute that poles bound with less than 3 ev would escape from the target.

The target below the region of proton impact acted as an absorber of low-energy electrons, so that bombardment by  $10^{12}$  protons could be made without producing severe background in the emulsions. No monopoles were observed. We therefore conclude that the cross section for production of Dirac monopoles of any mass less than protonic by 6.2-Bev protons on copper is less than  $1.5 \times 10^{-37}$  cm<sup>2</sup> per nucleon unless monopoles are bound in matter with an energy of more than 3 ev.

## III

A 3-mm-thick polyethylene target that had been bombarded in the Bevatron for an estimated integrated flux of  $10^{17}$  protons at approximately 6 Bev was placed 2.5 cm from nuclear emulsions and was then exposed to a 200-kilo-oersted field. No monopoles were found. We therefore conclude that the cross section is less than  $10^{-40}$  cm<sup>2</sup> per nucleon for the production of Dirac monopoles with binding energy between 3 and 20 ev in polyethylene.

## ACKNOWLEDGMENTS

The experiments were undertaken after a suggestion by Dr. Luis W. Alvarez. We wish to thank Dr. Edward J. Lofgren for his continued interest and assistance, and Dr. Joseph Lepore, Dr. Norman Ramsey, and Dr. John A. Wheeler for their counsel. We wish also to thank Dr. John Hornbostel, who check-scanned some of our emulsions after his own experiment (similar to our Part I) was stopped by the Cosmotron breakdown. The 200 kilo-oersted field was provided by Dr. Stirling Colgate and Dr. Harold Furth.

<sup>18</sup> See, for example, Norman F. Ramsey, Phys. Rev. **109**, 225 (1958).